DESIGN OF A FORCE-FEEDBACK TOUCH-INDUCING ACTUATOR FOR TELEOPERATOR ROBOT CONTROL

by

BRUCE EDWARD CALDER

Submitted to the Departments of
Mechanical Engineering and Electrical Engineering
in Partial Fulfillment of the Requirements
of the Degrees of

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

and

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1983

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ABSTRACT

A design of a force-feedback touch-inducing actuator, intended primarily for teleoperator robot control, is proposed. The design consists of tiny rubber air sacs inside a rubber glove, each connected by a thin pneumatic tube to a pressure source. The pressure in each sac is monitored by tiny pressure transducers which control tiny air valves, all of which are contained in a master multiplexer worn as an arm band. The design is analysed and a simple simulator design is proposed. The simulator facilitates parameter variations for design testing. The major mechanical components of the simulator are identified by catalog number from R.T. Engineering, Inc.

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I. INTRODUCTION

I.A The Problem

In June of , Professor Ken Sloan of the MIT Architecture Machine Group presented the following problem: A computer has generated the surface coordinates of an object in some well-defined region of space. The object can be displayed on a CRT screen and reflected by mirrors to produce a 3-dimensional image of the object in that region of space (see Figure 1). Build a device, perhaps some sort of glove, that enables one to "feel" the 3-dimensional object when it looks like one is touching (grasping) the image.

I.B Motivation

Sloan envisioned the use of such a device as a means of facilitating teleoperated robot control. If the device was built it could, in principle, operate in reverse; a real object could be grasped and the computer monitor the position and grip pressure of the hands. Supposing separate but connected devices applied to both the human operator's hands and the (assumed human-like) robot's "hands", any touch sensations "felt" by the robot (as the result of movements controlled by the operator) would be monitored and sent back to the operator for real-time touch inducement.

For example, a human operator sits before a 3-dimensional

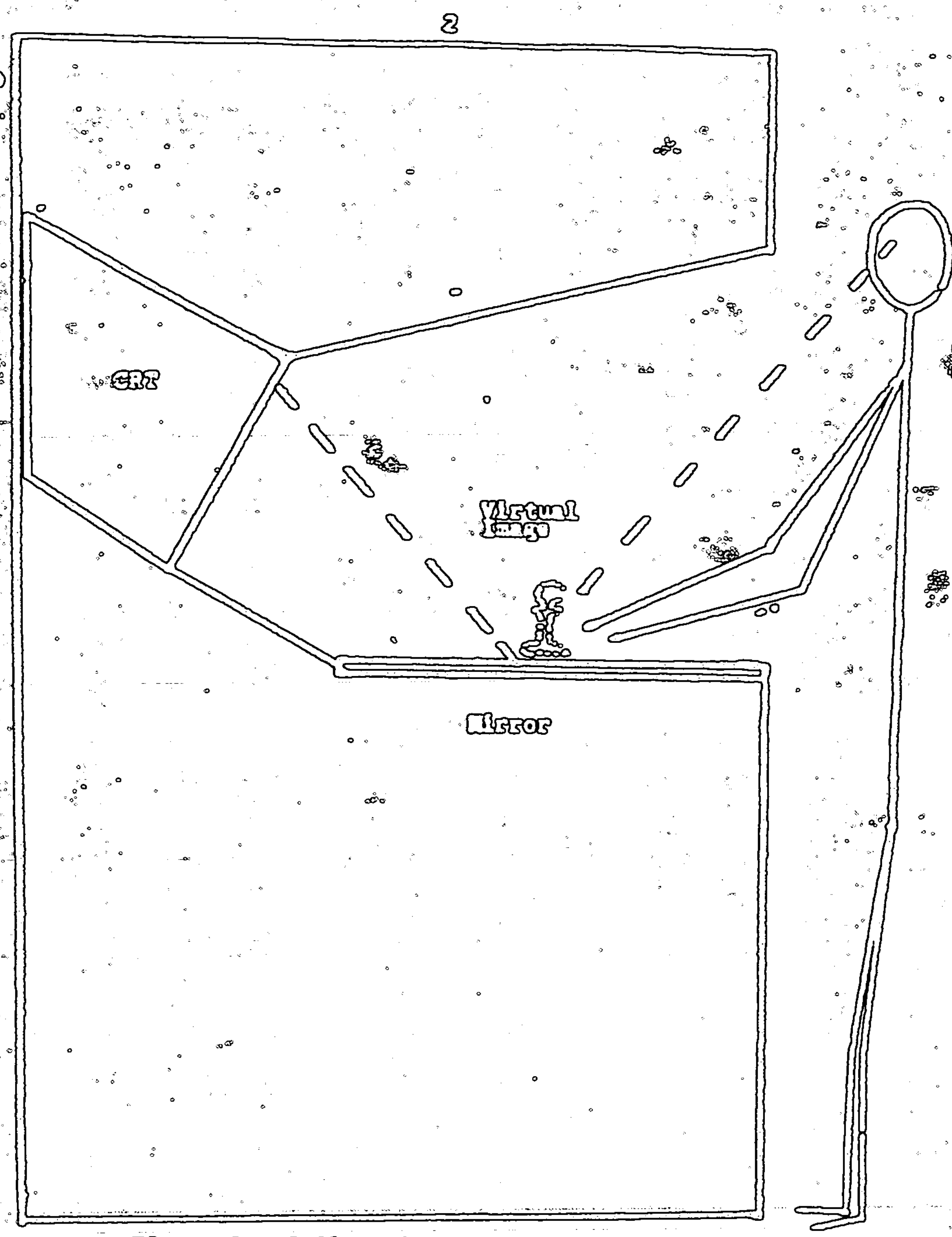

Figure 1: 3-Dimensional Computer Image Display

image of the robot's environment (as seen through the robot's "eyes" and displayed on a CRT and reflected as shown in Figure 1) and sees, say, the image of a screwdriver. The operator extends his hand as if to grasp the tool and the robot, at its remote location, follows his movements exactly. When the operator appears to be touching or holding the screwdriver, the robot really will be, and the touch sensations felt by the robot will be relayed back to the operator and induced in his hand. Thus the operator will see and feel the screwdriver as if it is real while, in fact, the robot, its environment, and the screwdriver may be thousands of miles away.

The realization of such a system--one that can translate the touch sensations felt by a machine to a human with sufficient resolution to be useful--would also introduce a very elegant approach to programming complex robot tasks. The method is based on the same feedback system within the human nervous system. One knows how to do something from experience (i.e. memorized touch-sensory and micro-movement information). One can, say, pick up a screw and know its orientation simply by touch. If the system could monitor the micro-movements and touch-sensations of a human while executing a task, then use the micro-movement signals to drive a human-like, touch sensitive robot until the touch sensations felt by the robot match the touch sensation signals from the human, the robot will do the same task.

As an example of robot task-programming, consider the problem of teaching a robot to pick a screw out of a bin and screw it into a hole a few turns. First a person performs the task: he knows how to pick out a single screw, position it in the hole, and turn it a few turns, purely by experience. The touch sensations and micro-movements of the human are transcribed into control signals and stored in computer memory. The robot then copies the human motion, guided by the micro-movement signals, in an effort to match its own touch-sensory signals with those from the human. Convergence of the touch-sensory signals means the robot has ultimately simulated the activity of the human, in this case placing the screw in a hole and turning it.

1.C Abstraction: The General Force-Feedback System

Sloan's problem is really a special case of a more general problem. In essence what is desired is a practical means of extending the motor and touch-sensory capabilities of a human to a machine (i.e. a robot). The key is "extension"; the data paths of such a system should not be unlike those of the human motor and touch-sensory nervous system. Nerves transmit information to the brain in the form of discrete impulses, the brain processes the information and controls the action of the muscles according to conscious and unconscious directives, and the muscles throttle the sensory-information by

physical movement. Therefore, the artificial extension system must contain three analogous components; a source of digital signals containing both macro-position and touch-sensory information, a central logic unit for data analysis, and a mechanism for altering touch sensations through physical movement. For this application the second and third components are a computer and the robot's mechanics, respectively. However, the first component requires signals from two sub-systems, a tracking system and a touch-sensitive actuation system. The actuation system is the main topic of this thesis.

The total system is illustrated, using a block diagram, in Figure 2. This is a system-level abstraction; each component is an independent (modular) sub-system that interfaces with the other sub-systems via the data paths. This system involves feedback control and since the control signals pertain to touch, which is a manifestation of force, it is called a "force-feedback control system".

1.D Force-Feedback Systems Analysis

The realisation of any force-feedback control system requires synthesis and integration of several sub-systems. For this case, whether the application be a teleoperated robot in real-time or a means of programming complex manipulator motions, at least two sub-systems are essential: a tracking system and an actuation system. The tracking system must transform position, orientation, and movement into

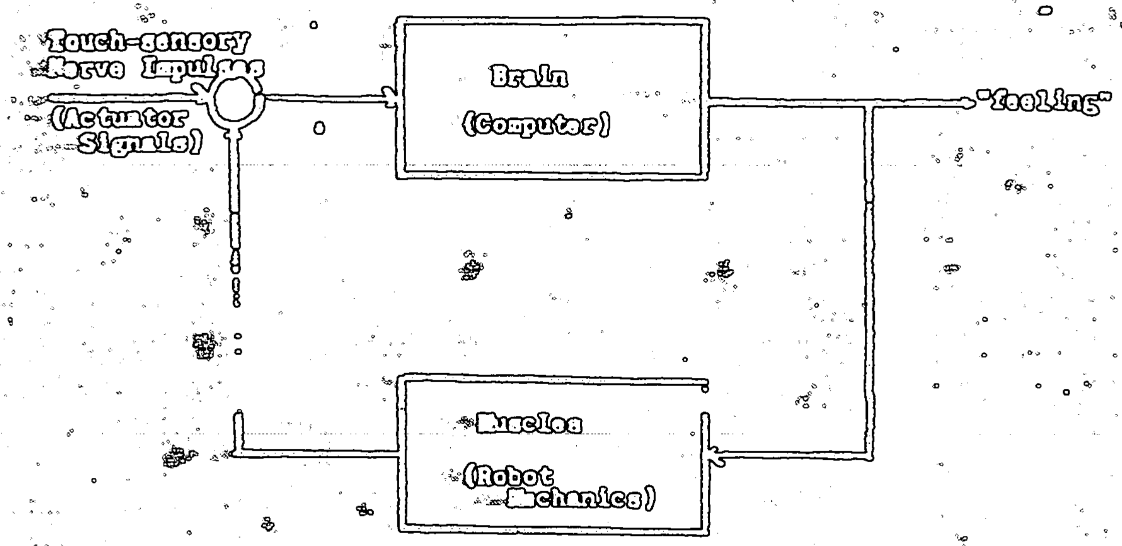

Figure 2: Block Diagram of Force-Feedback Control System

control signals, and vice-versa, for (perhaps real-time) static simulation by the robot, or human operator. The two sub-systems could be intricately coupled, making design of the actuation system dependent on the design of the tracking system, but good design strategy admonishes modularity so, henceforth, consideration of the actuation system shall be under the assumption that all other sustaining systems are available and independent of the actuation system itself.

I.B The Force-Feedback Actuation System

The force-feedback actuation system serves to interface the human operator and his environment with the robot and its environment. General design specifications require the two branches have some mechanism for dual and reversible operation; transduction of pressure levels into control signals and vice-versa (hence the term force-feedback). In addition, the two branches should be independent in that control signals to either branch can have any origin, not necessarily just from the other branch.

The operator's branch of the general actuation system can, in principle, apply to any domain, for instance, the entire surface of the human operator's body. The only practical way of realizing such a system is to design a modular and miniature force-sense-inducing mechanism such that an arbitrary number of such mechanisms can be combined in a 2-dimensional array, attached to a flexible substratum, and tailored to the

body like mall. This thesis focuses on designs of force-sense-inducing (actuation) mechanisms in accordance with that design philosophy. Many possible mechanisms are analyzed, most rejected, a few retained, but only one is developed and implemented as a working prototype.

The actuator I chose to develop was a tiny rubber air-sac connected by a long, thin pneumatic tube to an air supply. The design facilitated adhesion to a flexible substratum (a rubber glove), and independent, parallel, 2-dimensional array combination. The prototype consisted of air-sacs, one air-sac per finger pad, glued to the inside of a sturdy rubber glove. Pressure sensations could be induced in the fingers by injecting air into the sacs, expanding them against the finger, and pressure levels due to external forces monitored by measuring pressure waves along the supply lines. The air-sacs were fabricated from strips of rubber from surgeon's gloves. Only the actuation mechanism (the air-sac) was actually made and tested. A complete and fully automated (computer controlled) branch of the actuation system was never fully realized, but a feasible design is proposed in section III.C.

II. BACKGROUND

II.A Introduction

Many of the design problems of the force-feedback actuation system are the same as the "classic" tactile sensor problems under investigation in robotics research today. Teleoperated robots with no feedback control have existed for the past 35 years [6]. Only recently (say in the past 10 years) has much effort been made trying to produce intelligent, self-controlled, and task-oriented robots. The central problems that must be solved for robots to behave intelligently involve the development of some sort of tactile sensing ability. Tactile sensing alone is sufficient for self-controlled robots programmed to accomplish certain predetermined tasks, but more ill-defined, variable, or "custom" tasks must be controlled by a human operator, hence the need for teleoperator control. Teleoperation, however, requires both tactile sensing for the robot and some sort of touch-inducing mechanism for the operator (to communicate the robot's sensory information to the operator), hence the need for force-feedback, touch-inducing actuation. The requirements for both control systems are nearly the same. Since development of tactile sensors can be viewed as the first step in developing an actuation system (in addition to solving a pressing industrial robotics problem), most of the robotics literature addresses that area. Therefore, the

engineering requirements and specifications for tactile sensors were inferred from the works listed in the bibliography and used as guidelines for the design of my actuation system.

II.B Survey of Other Designs

Several modes of control have been developed for mechanical arms. There is the "manual mode" in which all control originates from some analog manual input from the human operator [6]. In this mode the most successful technique is the force-reflecting master-slave control widely used in industry. The mechanical arm has "give" to any external forces (primarily due to collisions with its environment) and thus warns the operator by blocking movement in that direction of motion. The program-controlled industrial robot mode is one in which the robot is programmed to endlessly repeat a fixed sequence of motions without operator intervention. This is successful when the task can be prearranged in space, time, and dynamic conditions in a given industrial environment. In this mode the robot cannot adjust to environmental changes because it does not sense them. Changes or variances in its work conditions cause the robot arms to stop or jam the work.

Current development efforts are focused on sensor-referenced and computer-controlled (SRCC) manipulators [6]. Some simple SRCC robots already exist. This advanced control mode has great potential to extend the use of mechanical arms far beyond the domain of strictly repeatable tasks. However, the

present state of SRCC manipulator technology is primitive [6]. The technology needed to realize the full potential of teleoperation is also necessary for SRCC robots. In addition to graphic display of sensory information, voice communication with the control system, and kinesthetic coupling between operator and mechanical arm. Unfortunately the latter three areas are nontrivial and the best, or at least most developed. Kinesthetic coupling was designed in 1980 and is described as a "general-purpose, force reflecting position hand controller" [6]. It consists of a mechanical boom that one grasps and tries to hold stationary. The forces and torques "felt" by a remote manipulator are transferred to the boom and one "feels" them by resisting the boom's motion. The system thus far is adequate, but is unable to transfer touch sensations which are potentially even more useful for teleoperator control. Proposals to combine force-feedback with touch sensations have been suggested but no suitable means have been developed. Two of the most likely candidates are tiny vibrating pins covering the hands like a glove, and tiny current source electrodes in a similar geometry. Both can simulate touch, not force, but their flexibility is limited and their implementation difficult, in addition to providing unrealistic sensations. Otherwise, very little progress in kinesthetic man-machine coupling has been made, hence the motive for this thesis.

II.C Design Requirements

Design requirements for the actuation system are not unlike those of tactile sensors. According to a recent survey, about 90% of questioned industry indicated a desire for robots with tactile sensing capabilities and listed the desireable features [1]. Old tactile sensors included strain gauges, conductive rubbers, limit switches, and RCC (remote-center-compliance). However, these methods proved insufficient, mainly because the information was noisy and too voluminous to be useful. As a result of industry's experimentation with many "simple" designs, three of the "most desireable properties" of tactile sensors were consistently mentioned in the survey: the tactiles should be skin-like, the sensors hand-like (however, according to MIT professor Warren Seering, sensors should not necessarily be hand-like because human hands are not optimal for most industrial uses), and the entire manipulator intrinsically "smart" at the sensor level.

Whatever mechanical sensors are used, flexible, durable, and tactile skin can be wrapped around them. "Smart skin" could be sold by the square meter or molded to order in special configurations. In any case the artificial skin should have high sensitivity, fast response, continuous variable output, require little power, and be cheap and durable. Skin toughness requirements could vary considerably depending upon the application. Other forms of intelligence

were suggested, such as temperature and humidity sensitivity: the former for distinguishing materials (metals, plastics, cloth) and the latter for incipient slip estimation.

A cord containing many hundreds or even thousands of wires emanating from the manipulator is unacceptable. Massive signal flow simplification could be done at the "hand" by distributed-logic arrays and processed (or multiplexed) so only a few output signals need go to the CPU, via a few wires or electromagnetic transmission.

III. DESIGN OF THE FORCE-FEEDBACK TOUCH-SENSE-INDUCING GLOVE

III.A Design Strategy

The very first design steps involved analyzing the problem from an abstract system-level perspective as outlined in the Introduction. This clarified the problem and illustrated how the entire system could be segregated into independent sub-systems. For this case the main sub-systems were the computer, the robot mechanics, the tracking system, and the actuation system. I chose to concentrate on the actuation system because it was the least developed of the four areas in terms of over-all research and development. The tracking system, as mentioned in section II, is a potentially complex problem that has myriad design possibilities depending on the application and present day technology. Robot mechanics, such as the design of a mechanical hand, is also very complex, and mechanical "hands" are now available from several sources [6]. Needless to say, computers are complex as well and significant advances are made every year in speed and capacity. Therefore, I chose to design the actuation system independent of the other sub-systems with the expectation that the other sub-systems would be available for integration when needed.

III.B Early Designs and Analysis

As mentioned in section I.E, the only design constraints on the actuator itself (the mechanism that can both induce

pressure sensations in one's skin proportional to the pressure on the robot and relay information about pressure on the skin back to the robot) were also, modularity, and adherence. With that in mind the first design conception involved electrostatic force as the means of inducing touch, and electrical capacitance as a means of monitoring external pressure. The design was unacceptable for at least two reasons; by its very nature it was not miniature or modular enough, and the force induction was exceedingly weak. A glove was envisioned that consisted of some kind of conducting material. Each strip of material on the inside, sensitive, part of the fingers was insulated from the rest of the glove, the idea being electostatic attraction would induce force on the fingers when a voltage was applied (see Figure 3) and the capacitance monitored proportional to the deformation geometry caused by any external forces. An order-of-magnitude calculation quickly showed the futility of any design based on electrical forces alone.

An optimistic approximation of the maximum electrostatic force one could expect was obtained by considering the attractive force of two charged, infinite, parallel, conducting sheets (see Figure 4). Charged parallel plates of area A separated by distance d and sandwiching a medium of permittivity ϵ has a capacitance C when a voltage V is applied. The capacitance is given by

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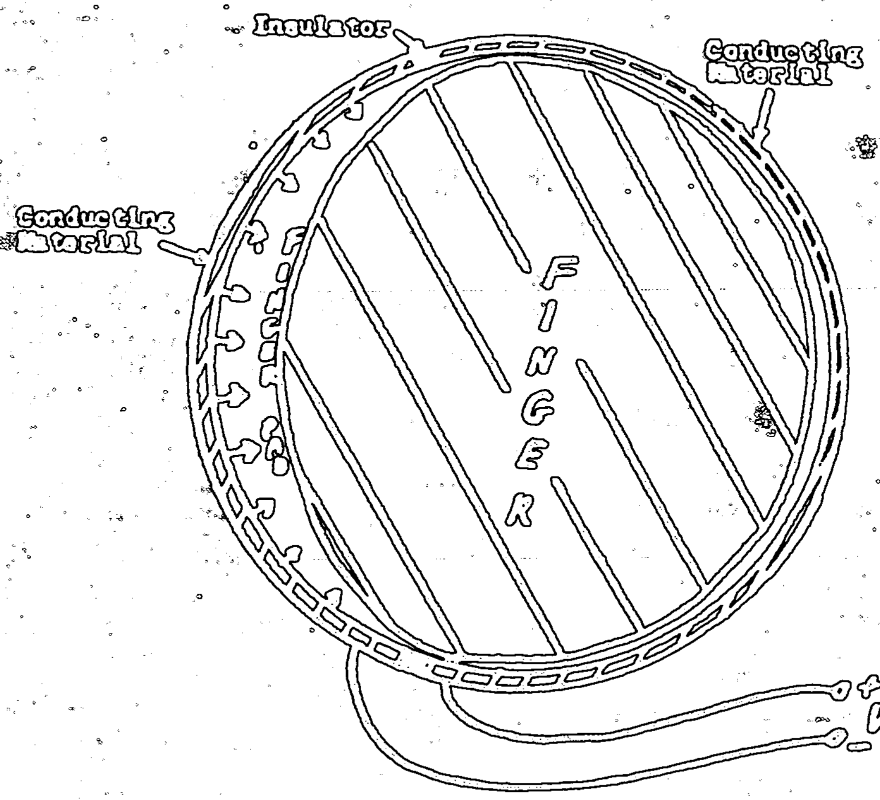

Figure 3: Idealized Cross Section of Electrostatic Actuator

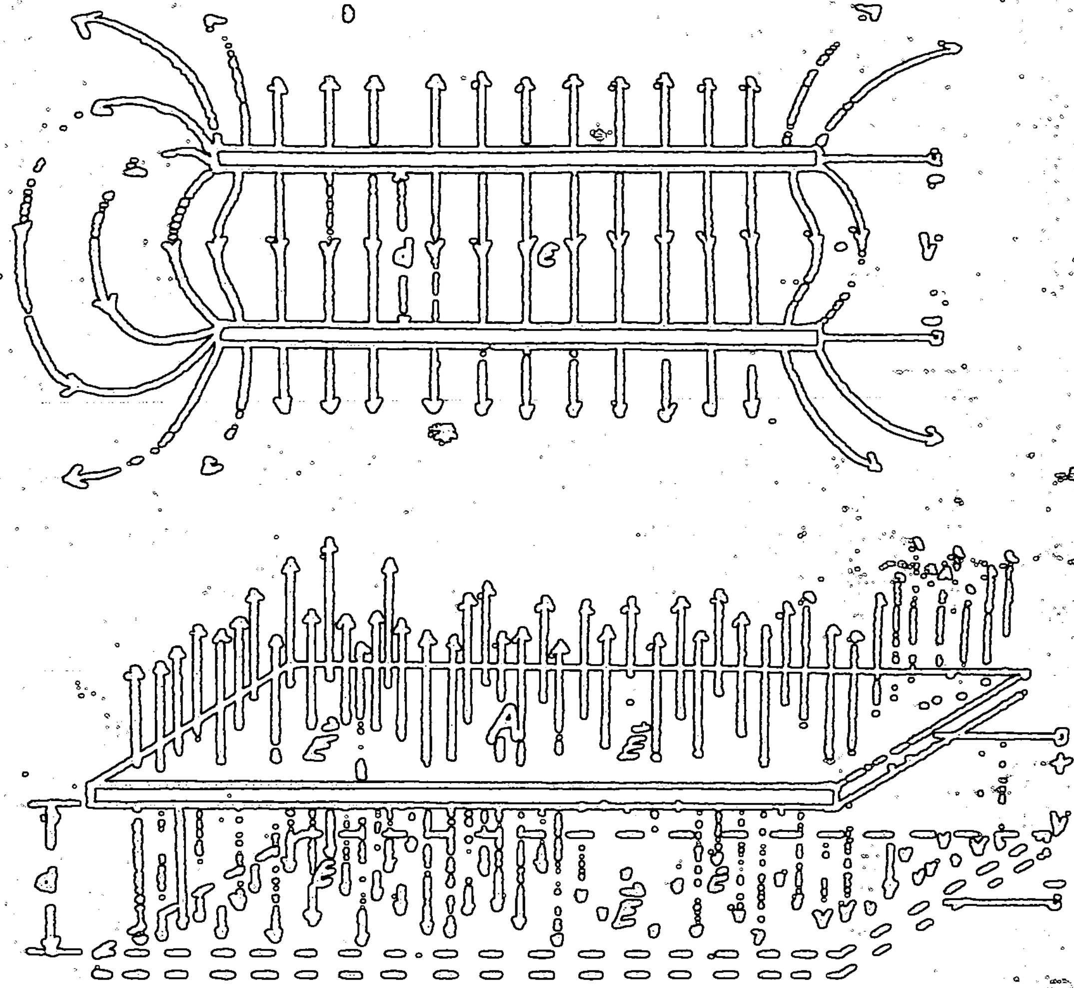

Figure 4: Parallel-Plate Approximation of Electrostatic Actuator

$$C = \frac{q}{V} = \frac{\epsilon A}{d} \qquad (1)$$

and the force between the plates is given by

$$|F| = q|E| \qquad (2)$$

where E is the electric field present in the absence of one of the plates and q is the net electric charge on the "absent" plate. Therefore, $q=CV$ and $E=\frac{V}{2d}$ yielding

$$F = \tfrac{1}{2}\epsilon A\left(\frac{V}{d}\right)^2 \qquad (3)$$

If $A \sim 1$ cm^2, $d \sim 1$ cm, $\epsilon \sim 10^{-9}$ F/cm and we require a force induction of at least .1 lb then V must be at least 10 KV. Clearly, any device based on similar physics is physically impractical.

The motivation behind the electrostatic design was primarily a first attempt at some means of inducing touch sensations. However, even if the design was feasible the touch-area resolution would have been poor. The next design addressed the resolution issue directly and used electromagnetics as the force source. Again a glove was proposed, this time made of nonconducting material, embedded with arrays of tiny magnetic "pistons" each surrounded by its own current coil (see Figure 5). The action of each piston could be controlled by the current through its coil; one direction for retraction, the other for ejection, and with a force, presumably against the skin, proportional to its magnitude squared.

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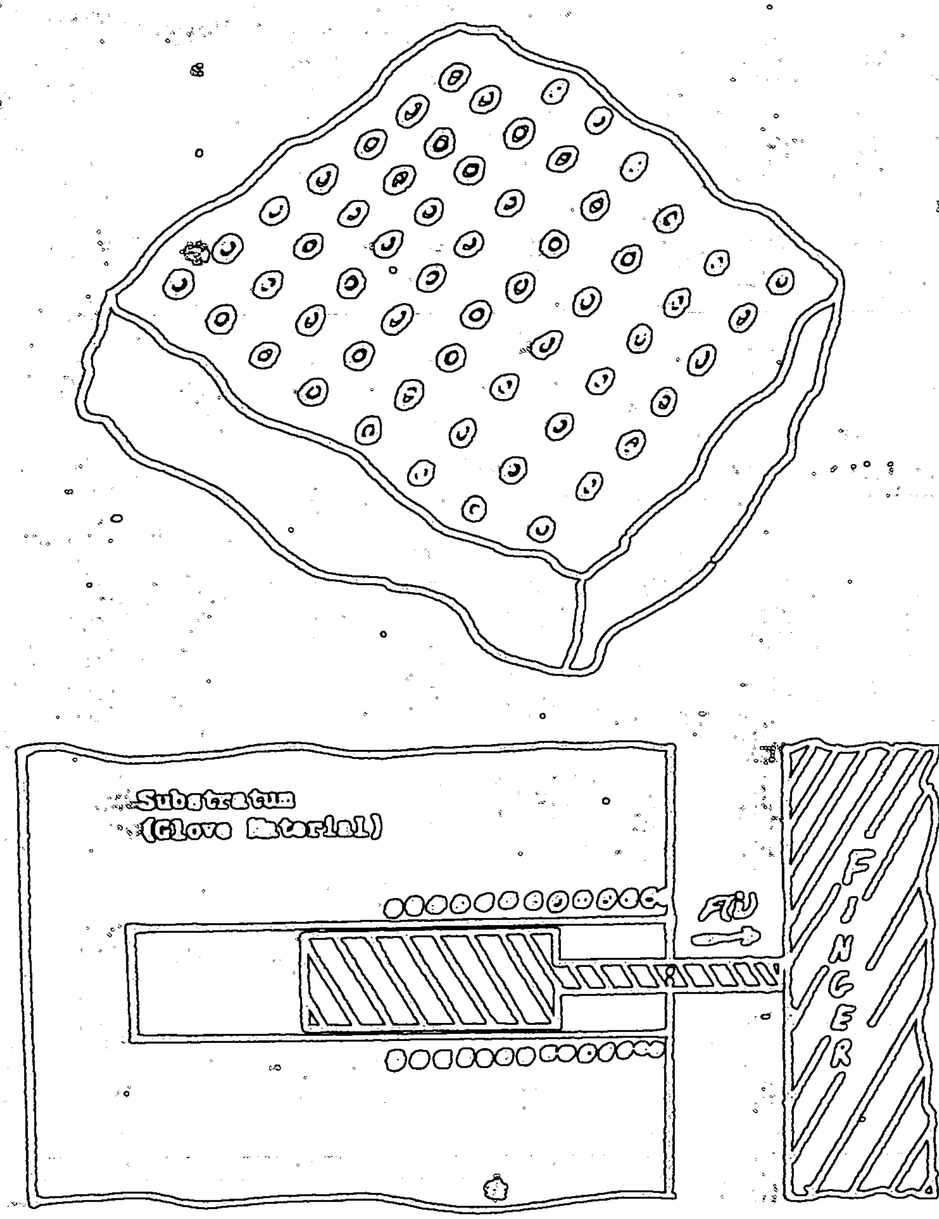

Figure 5: Substratum with Arrays of Actuators
Cross Section of Actuator

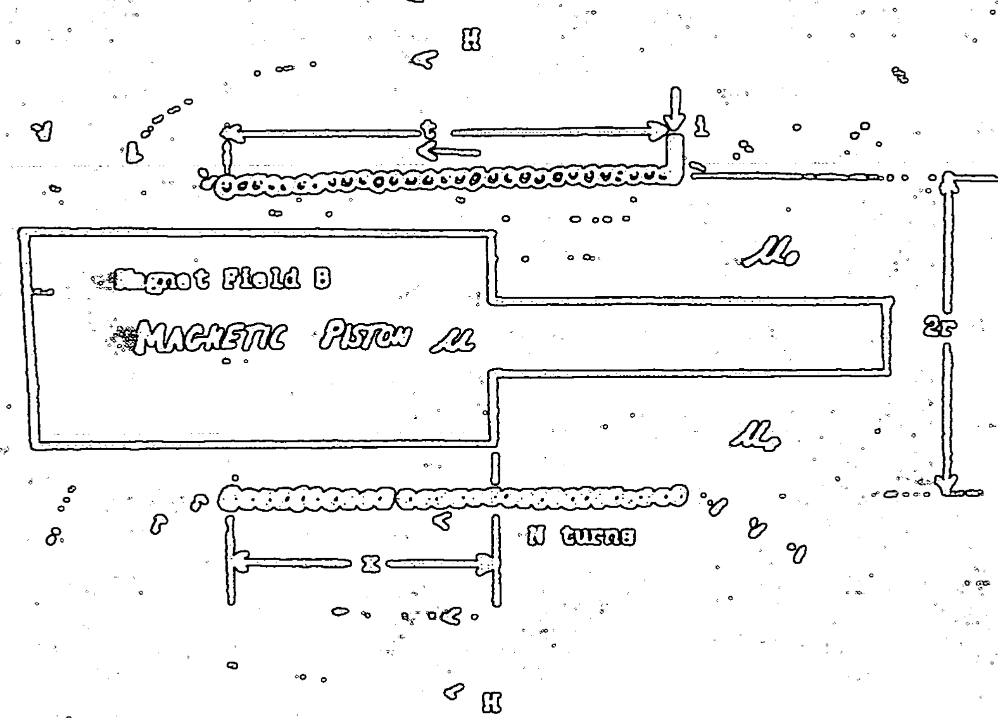

Figure 5: Schematic of Solenoid Actuator

Unfortunately, this design was riddled with problems ranging from insufficient force induction to enormous signal processing rate requirements. Both obstacles can be explained using the explicit equation for the piston's inducing force as a function of current.

Figure 6 shows a schematic of the solenoid and all its parameters. Modelling the system as a conservative energy transducer, the ejection force F of the piston on the finger is [11]

$$F = \frac{\partial W}{\partial x} \tag{4}$$

where W is the potential energy of the solenoid. Modelling the elements as ideal and neglecting resistance and inertia, W becomes

$$W = \tfrac{1}{2}L(x)i^2 = \tfrac{1}{2}\lambda(x)i \tag{5}$$

where $\lambda(x)$ is the magnetic flux linkage along the axis of the solenoid as a function of x. Magnetic flux linkage is the total magnetic field within the coil and varies with x because the magnitude of the field varies considerably going from the magnetic piston to the air.

$$\lambda(x) = \pi r^2\left[\frac{N}{t}(\mu H + B)x + \frac{N}{t}(t-x)\mu_0 H\right] \tag{6}$$

where r is the radius of the solenoid coil and t is its length, N the number of turns, μ the permeability of the magnet and μ_0 of free space, B the permanent magnetic field

density, and H the induced magnetic field from the current coil. From Ampere's Law

$$H = \frac{Ni}{2t} \qquad (7)$$

Substituting Equations 5, 6 and 7 into Equation 4 yields

$$F = \frac{N\pi r^2}{2t}\left(\frac{\mu N i^2}{2t} + Bi\right) \qquad (8)$$

assuming $\mu >> \mu_0$. For sufficiently large B the direction of piston movement (injection or ejection) is governed by the direction of the current i. If N=20 turns, r=0.5 mm, t=5 mm, $\mu = 10^3$ H/m, B=100 Gauss, the current must be at least $i = \frac{2Bt}{\mu N} = 50$ mA to assure piston retraction. Assuming a forward current of 100 mA, the maximum force one could expect is 2×10^{-5} Newtons (larger currents would introduce serious power dissipation problems). Therefore, one can see the nonlinear force-current relationship and its insufficient force capabilities makes this design impractical.

III.C Survey of Possible Designs

An impasse seemed to be reached. The two most obvious sources of force induction (electrostatic and electromagnetic) proved too weak, besides not providing any means of force-feedback. Brainstorming for new designs produced a variety of unorthodox concepts, unfortunately most required nonsubsistable materials and unrealistic idealizations. The most difficult problem was finding a means of both sensing external

pressure levels and inducing pressure sensations from external signals. At one point I considered changing the problem to one of designing a tactile sensor and touch inducer separately, which is still a viable alternative. The tactile sensor would monitor sensations of the robot and the touch inducer would induce the robot's sensations in the operator's hands. However, in keeping with the original design goal, two very different designs ultimately prevailed; one very "blue sky", the other the subject of this thesis.

The blue sky design is undoubtedly the most elegant solution to the problem thus far conceived. Upon investigating the use of current-source electrodes to induce point-touch sensations, I questioned the need for any artificial actuation system at all. Rather than build a device that tracks macro-movements and monitors and induces touch sensations, why not read the information directly from the nerves? Motor information from the brain could be tapped and processed into control signals for robot simulation. Sensory information travelling to the brain could be tapped and stored for robot-task programming (as previously described). Sensory information "felt" by the robot (this requires a sophisticated tactile sensor but need not be a force inducing actuator) could be processed into nerve impulses and sent to the brain for interpretation. Hence a human operator could control the movements of the robot by his own actions, but feel the robot's "feelings" (environment) rather than (or in addition to) his own. All that would be

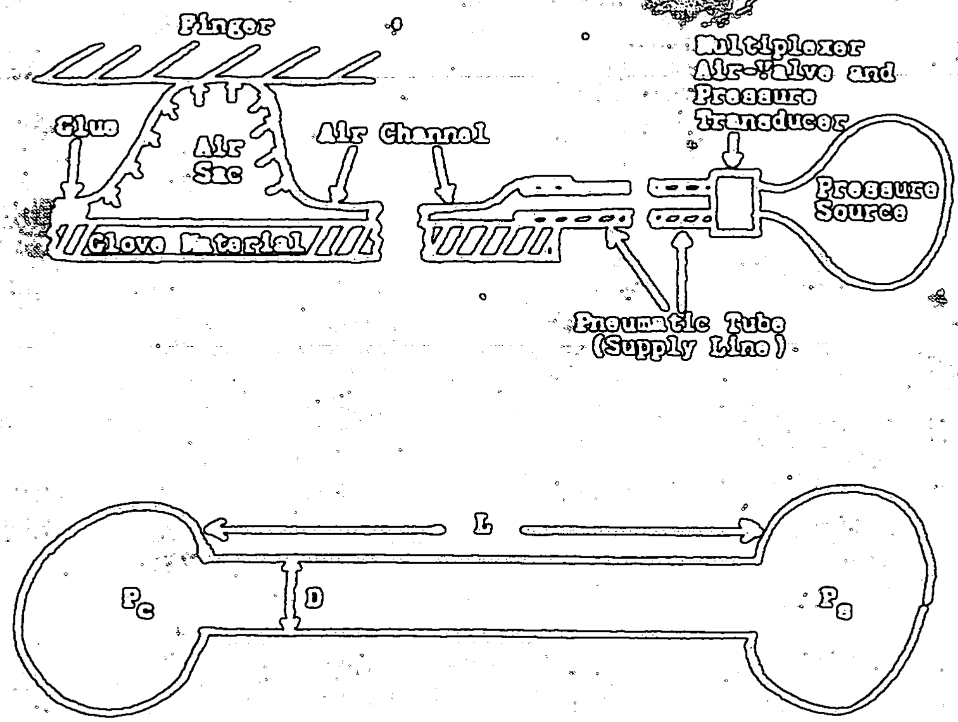

Figure 8: Schematic Cross Section of Single Actuator
Engineering Abstraction for Analysis

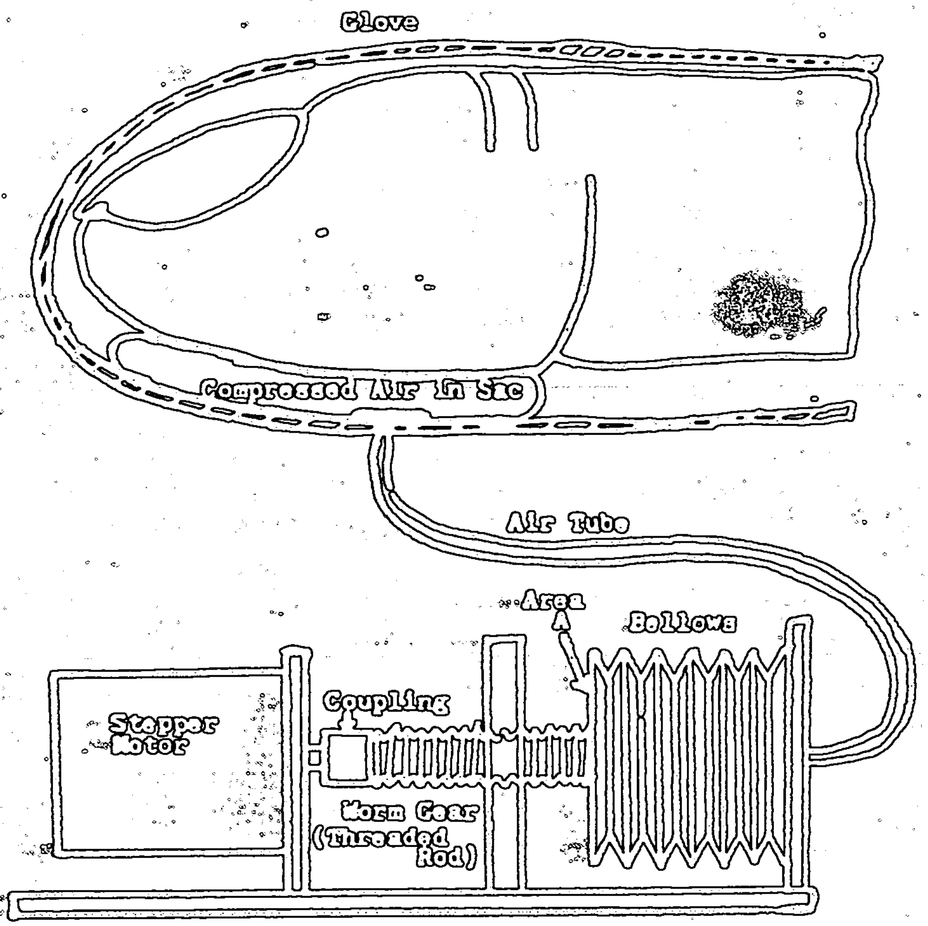

Figure 9: Schematic of Prototype Model

A schematic of the prototype model is shown in Figure 9. The stepper motor receives control signals from the computer in the form of two bit bytes. Each byte sequence represents one of four possible instructions: 00 for zero (or vacuum) pressure (no feeling), 01 for light touch, 10 for medium pressure, and 11 for hard pressure. A driver board receives the computer instructions and processes the information into control signals for the stepper motor to execute. The driver board must know what position the motor is in to execute the instruction (e.g. going from 11 to 01 is different than from 10 to 11) and must satisfy certain stability and performance criteria.

The stepper motor drives the bellows via a worm-gear (threaded rod). This provides definite air displacement with motor rotation, mechanical advantage for the motor, and easy construction and analysis. Flexing of the bellows causes a pressure differential ΔP which transfers air to or from the air sacs. This model enables one to test response times and system behavior as functions of air tube diameter, source pressure, and sac sizes.

Construction of the prototype requires certain approximate specifications. Since the air sac covered the index finger pad, its volume, when fully expanded against the finger, was about 4 cm^3. A response time of 100 msec means a flow rate of 40 cm^3/sec. The equation for isothermal viscous flow through a circular pipe is given by [10]

$$\Delta P = \sqrt{\frac{16\eta k T Q \rho L}{\pi m R^4}} \tag{9}$$

where ΔP is the differential pressure in Dynes/cm^2, η air viscosity, k Boltzmann's constant, T absolute temperature, Q flow rate, ρ air density, L tube length, m molecular air mass, and R the tube's radius. At STP, Equation 9 can be approximated to

$$\Delta P \approx \sqrt{\frac{10^{-9} Q L}{R^4}} \tag{10}$$

The prototype model requires Q to be 40 cm^3/sec. I planned to use a 10 foot (300 cm) long polyethylene air tube with inside diameter 1.68 mm (i.e. R=.084 cm). Such parameters required ΔP to be about 7 psi. Scaling this analysis to the multiplexer design, and keeping Q=40 cm^3/sec but letting L=50 cm and R=.05 cm, we find $\Delta P \approx$ 8 psi. Therefore, a 10 psi pressure source would do nicely.

Actual construction of the prototype requires quantization of certain specifications. Selection of the stepper motor and its corresponding driver board depends upon its power requirements. To estimate the power required by the motor to drive the bellows and produce a pressure differential, one must consider its speed and torque requirements.

$$\text{Power} = \text{Torque} \cdot \text{Speed} \tag{11}$$

The speed depends upon the bellows geometry, the worm-gear, and the flow rate desired.

$$\text{Speed} = \frac{Q}{Ar\tan\alpha} \tag{12}$$

where Q is the flow rate, A the area of the bellows, r the radius of the worm-gear and α the pitch angle of the threads. The torque depends on the forces on the worm gear. Figure (10) shows the forces on the threads and the torque T required to balance them.

$$T = (f\cos\alpha + N\sin\alpha)r \tag{13}$$

$$W = N\cos\alpha - f\sin\alpha \tag{14}$$

$$\frac{P}{2\pi r} = \tan\alpha \tag{15}$$

$$f = \mu N \tag{16}$$

where f is the friction force on the threads, N the normal force, r the worm-gear radius, α the pitch angle, P the pitch (typically in threads/inch), and W the force due to the pressure differential ($= \Delta PA$). Combining Equations 13 through 16 gives

$$T = \frac{Wr(\mu\cos\alpha + \sin\alpha)}{(\cos\alpha - \mu\sin\alpha)} \tag{17}$$

$$= Wr\tan(\alpha+\beta) \tag{18}$$

where $\beta = \tan^{-1}\mu$, and μ is the coefficient of friction of the threads. Combining Equations 12 and 18, the power requirement for the motor becomes

$$\text{Power} = \Delta PQ\,\frac{\tan(\alpha+\beta)}{\tan\alpha} \tag{19}$$

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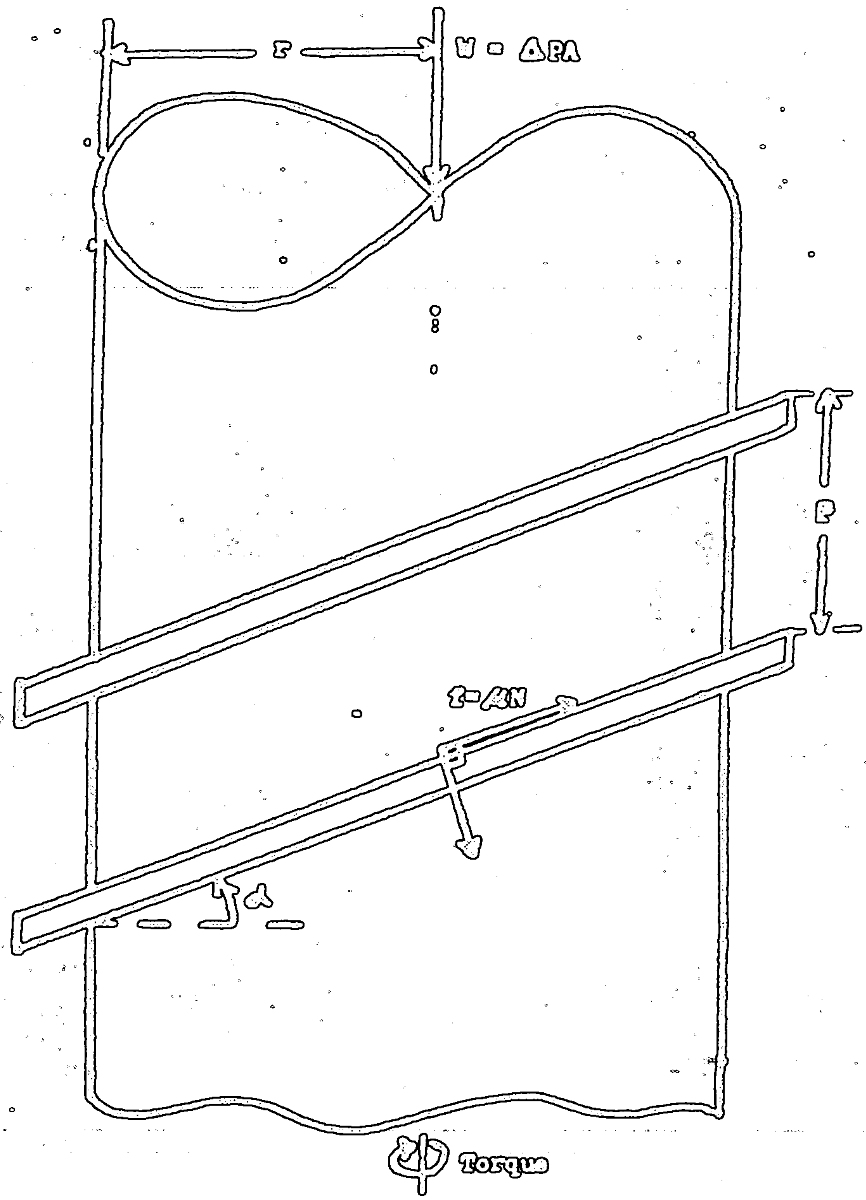

Figure 10: Worm Gear Analysis

Therefore the power requirement for a threaded rod is minimized with maximum α and minimum β. A $\frac{3}{8}$" threaded rod of 18 threads/inch gives an $\alpha = \tan^{-1}\left(\frac{p}{2\pi r}\right) = .071$ rad ($\approx 4^{\circ}$) and if $\mu = 1$ then $\beta = .785$.

If $P = 10$ psi and $Q = 40$ cm^3/sec ($= 2.4$ in^3/sec), then the power requirement is less than 50 Watts. If we assume a bellows with cross sectional area $A = \pi\, in^2$ then the torque is 72 oz·in and the required RPM's (=speed x $60/2\pi$) is 820 (=14 rev/sec). These are not extreme requirements for stepper motors.

A complete set of hardware sufficient to implement the prototype was obtained from R.T. Engineering Service Inc. (171 Forbes Blvd. Mansfield, MA 02048). The set included an M062FD09 72 steps per rev. stepping motor, a DRD002A driver board, PSD048 48 volt power supply, a LUS-10-12 12 volt power supply, and a CHD040 6" long 20-20 pin connection. The motor can be mounted and attached to the threaded rod. The threaded rod interlocks with a bellows mount. A polyethylene tube connects to the bellows and leads to the air sac in the glove.

IV. CONCLUSION

IV.A Summary

A force feedback actuation system is an artificial touch-sensory extension system. Its primary use is for teleoperated robot control and a means of programming complex robot tasks. The system is composed of four parts: the robot's mechanics (e.g. mechanisms, manipulators, joints, etc.), a central computer, a tracking and motor control system, and a touch-sensory feedback system. The four subsystems can be modularized not only conceptually but as a design aid. Only the touch-sensory feedback system was considered in this thesis. A design was proposed that enabled one to feel the pressure sensations "felt" by a robot and to store touch-sensory information felt by an operator for later duplication by a robot, in its effort to simulate the operator's dexterity. Several plausible designs were proposed and all but two were unacceptable; one was too advanced, and the other was developed in this thesis. The developed design consisted of small rubber air sacs glued inside a rubber glove. The air sacs could induce pressure sensations by expanding them with air, and external pressure on the hands could be monitored by noting the net pressure change in the sacs. The proposed design included a pneumatic multiplexer and multiple pressure transducer worn as an arm band. Air from a main supply hose would be multiplexed according to the incoming control signals

and the transducers would generate both feedback control signals for the multiplexer air-valves and external control signals, presumably for the other branch of the actuation system.

A prototype model was partially constructed to test the proposed design. The prototype consisted of a single air sac glued inside a rubber glove connected by a thin plastic tube to a stepper motor driven bellows-pump. Analysis of the prototype produced specifications necessary for purchasing useable equipment. The analysis also showed the feasibility of the proposed design. Assuming a response time of 100 ms and air channels of 1 mm diameter, a pressure source of 10 psi would suffice. Ten psi induced across the whole hand would simulate a force of 200 lbs. The air sacs induced a very believable force for flat object simulation. Pressing one's finger against a table top while wearing a glove felt very much like an expanded air sac inside a glove.

The pneumatic design satisfied many of the design requirements mentioned in II.C. The design was skin-like and durable whether it consisted of sacs within a sturdy glove or sheets of sac-filled rubber. The glove design facilitates human hand-like manipulators, and the generic sheets can cover any other type. The system is "smart" by means of the arm band multiplexer and only two cords need lead to it, a wire bundle and an air tube. Sensitivity needs improvement but response time and continuous-variable output are both realized. The power requirement for this design is fairly irrelevant since

pneumatic pressure can be generated efficiently and in abundance, and transferred anywhere. The design is as durable as the materials involved, and there are no moving parts. Manufacturing costs are difficult to predict, but I suspect they would be very small compared to those for other designs.

IV.B Recommendations

Touch-area resolution, which is a measure of touch sensitivity, is the major area in need of improvement for this pneumatic design. Increasing the number of air sacs per finger pad (or unit area) might work, but I am not sure how that would feel. Probably no one mechanism is capable of simulating the surface of a general object, so one should combine different touch-inducing techniques. Other forms of sensory stimuli can be induced as well, such as temperature.

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